Die radiotoxischen Risiken von Reststoffen aus der Kernfusion werden in mehreren Forschungsprogrammen wie z.B. SEAFP (Safety and Environmental Assessment of Fusion Power, 1992 bis 1995) und SEIF (Safety and Environmental Impact of Fusion, 2001) mit denen aus Kernkraftwerken sowie mit denen der Spurenelemente aus mit Kohle befeuerten Kraftwerken verglichen. Die im Jahr 2005 abgeschlossene Power Plant Conceptual Study (PPCS) untersucht dahingehend 4 Modelle – mit A bis D bezeichnet – eines Fusionskraftwerks.

Im vorliegenden Beitrag werden die Ergebnisse zum Modell B mit denen aus der Kernspaltung und Kohleverbrennung verglichen. Schwerpunkt bilden die anfallenden Reststoffe. Vergleichsmaßstab für das Risiko der betrachteten Massenströme ist die Radiotoxizität des angereicherten Urans vor dem Einsatz im Kernreaktor sowie der Reststoffe aus der Kohleverbrennung.

Ein offensichtliches Ergebnis der PPCS-Studie im Vergleich zu älteren Studien sind neuere Erkenntnisse zu Ingestitions- und Inhalationsrisiken, die sich aus der Berücksichtigung von Werkstoffverunreinigungen sowie anderen Randbedingungen ergeben. Ein wichtiger Aspekt betrifft das Vorhandensein von Aktiniden in den Reststoffen der Kernfusion.

Comparison of environmental impact of waste disposal from fusion, fission and coal-fired power plants

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1. Introduction

In context to the Directive Com(2010)618 on the management of spent fuel and radioactive waste proposed by the *European Commission*, in order to find concepts which are acceptable to the public, it is important to concentrate research at the nuclear power sector on options with low radiotoxic impact concerning disposal of waste. In this aspect, fusion power has advantages against fission power as no long-lived radioactive nuclear reaction products are produced. However, activation at structural materials of the reactor takes place. As the environmental impact of radioactive waste can decide public acceptance of fusion power, it is important to clarify this impact to the public as well as to governments and to achieve a broad consensus in time.

The disposal of coal ash also brings about an environmental impact because of chemical hazards such as mercury and arsenic, but also because of radiotoxic hazards such as uranium and thorium.

In order to assess the environmental impact of power plant waste, not only the masses or volumes of this waste are relevant, but also the activity. A coal-fired power plant brings about higher masses of ash, compared to fission waste at the same electricity generation. Nevertheless, the activity of fission waste is higher. Additionally, it has to be taken into account that the toxicity of some nuclides is much higher than that of others, based on the same activity. Therefore, in order to assess the overall toxicity of waste, dose coefficients (committed effective doses per unit uptake for ingestion and inhalation in Sv/Bq) have to be taken into account on a nuclide by nuclide basis.

Using ingestion and inhalation dose coefficients for the assessment of radiotoxicity is a theoretical approach which can be used for illustration purposes. However, besides the production of pollutants, also pathways to the food chain and the atmospheric dispersion of pollutants is of relevance. The dispersion of coal ash in a ground-level repository is easier than that of nuclear waste in a deep geological repository. However, these aspects are not addressed in this paper, it concentrates on the production but not on the dispersion of wastes. Also the categorization of waste into not recyclable, complex recycling, simple recycling or hands-on is not addressed.

1.1 SEAFP

The environmental impact of fusion power has been an issue in many research programs, publications and information campaigns.

A website of the *European Commission* [1] among others addresses research on safety and sustainability of fusion power. It is stated that in less than 100 years the residual activity of waste from a fusion power station would be less than the radiotoxicity found in the waste from a conventional coal-fired power station. This is based on major conclusions reached by the team of SEAFP (Safety and Environmental Assessment of Fusion Power) in 1995 [2]. The development of radiotoxicity indices for different options is shown at *Figure 1*. Fusion model 1 with vanadium alloy structures and helium cooling reaches the coal ash level significantly before 100 years, fusion model 2 with low activation steel structures and water cooling after final shutdown some 500 years.

1.2 SEIF

In 2001 these results have been updated by a study on safety and environmental impact of fusion (SEIF) [3]. The study

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After activation induced by fusion neutrons, the FISPACT output files show, for each of the 194 cells, the development of masses, activities and toxicity figures for each nuclide as specific figure per kg of cell mass. By multiplication with respective cell masses, the total mass, activity and toxicity figures can be calculated on a nuclide-by-nuclide basis.

5. Power plant options

Key data of the fusion, fission and coal-fired power plant options used for the comparison at this paper are described in the following.

5.1 Fusion power plant

FISPACT output files and figures of the total masses (in kg), specific activity (in Bq/kg) as well as ingestion and inhalation toxicities (in Sv/kg) for each of the 194 cells of the PPCS model B fusion power plant have been obtained from the *Culham Centre for Fusion Energy*, Mr. *Raul Pampin-Garcia*. The figures are based on the 2001 update of EASY biological hazard data.

The masses are shown in *Table 2*. Based on the lifetime assumptions, the divertor has to be replaced 9 times. Including the final disposal of the divertor 10 times the divertor mass has to be disposed as waste within the lifetime of the fusion power plant.

The PPCS model B assumes some 480 tons of beryllium, some 2,400 tons are used during the fusion power plant lifetime if no recycling of beryllium is applied. From material specifications a uranium content of some 32 ppm can be assumed which brings about that some 77 kg of uranium is exposed to neutron radiation during the fusion power plant lifetime.

Adding all plutonium isotopes at all cells from the FISPACT output files, it is evident that some 4.7 kg of plutonium is produced within the 5 years operation time of the blanket and is present in the inventory of the reactor at the end of this period. This plutonium is spread at a low concentration of some 10 ppm over the beryllium and, therefore, cannot be separated from the beryllium. Assuming no recycling of beryllium, this corresponds to the production of some 23 kg of plutonium within the 25 years fusion power plant lifetime (this plutonium mass is of course not simultaneously as inventory in the reactor). Some 30% of uranium is transmuted to plutonium and , by a smaller extent, also to other actinides.

Based on these figures, the activity as well as ingestion and inhalation toxicity of total waste of the fusion power plant are calculated. There might be a significant potential to decrease the plutonium mass as well as ingestion and inhalation hazard of fusion power by optimizing the material impurities in the material used for the reactor or by decreasing the required beryllium mass. By arranging the tritium breeding pebble beds perpendicular instead of parallel to the first wall and filling the backspace of the breeder zone with breeder canisters instead of beryllium pebbles, the beryllium mass inventory can be reduced to 284 tons [10].

5.2 Fission power plant

Based on a net efficiency of 37% of a pressurized water reactor an amount of some 660 tons (equivalent to a thermal energy of 792 TWht) of enriched uranium (4.2% enrichment, 50 GWd/ton) is required to generate the same amount of electricity (292 TWhe) as the fusion power plant. Calculations of burnup and the development of ingestion toxicities have been performed by *Joseph Magill* et. alt. [11]. Plutonium and other actinides are produced by transmutation reactions, some 7.3 tons of plutonium equivalent to some 1% of the uranium amount are left in the waste.

For this paper similar calculations are performed using the decay engine of the *Nucleonica* website [12]. For the calculation of ingestion and inhalation hazard figures of ICRP 72 are used. This is different from the database used for fusion and coal ash. Some dose coefficients (for example Rn-222) are neglected. Therefore, it is expected that the fission results would be higher if the EASY biological hazard data would have been used. Nevertheless, the fission results are approximately comparable to fusion and coal ash to a certain extent. The activity of low active waste from a fission power plant is not taken into account.

The main calculations are based on an open fuel cycle without reprocessing of wastes. For a sensitivity calculation, a recycling of 99.5% of the plutonium is assumed. For another sensitivity calculation, additionally a recycling of 90% of the americium is assumed by means of partitioning and transmutation as it might be feasible for future fission reactor designs. Recycling of curium is not taken into account. By additional recycling there might be a potential to decrease the ingestion and inhalation hazard of fission power plants.

5.3 Uranium used for the fission power plant

Natural uranium, before mining, has already some radiotoxicity. After mining, the uranium used for the fission power plant is enriched to some 4.2% U-235. The residual depleted uranium is disposed. The toxicity of those nuclide masses of the natural uranium which are transferred to the depleted share is not changed by the fission power plant. The input of the fission power plant is only the enriched share. The output of the fission power plant is the waste described above.

It is interesting to investigate at which time the toxicity of the fission power plant output has reached that of the fission power plant input which can be used as a reference figure. Therefore, the activity as well as ingestion and inhalation toxicities of the enriched uranium including daughter nuclides before use in a fission power plant is calculated at *Table 3* based on the 2001 update of EASY biological hazard data.

5.4 Coal-fired power plant

Based on a net efficiency of 46% an amount of some 78 million tons (equivalent to an energy of 635 TWhNCV) of standard coal (net calorific value 29.3 GJ/ton) is required to generate the same amount of electricity (292 TWhe) as the fusion power plant.

The content of radionuclides depends on the origin of coal. A publication of the U.S. Geological Survey [13] reports that both the uranium and thorium concentration in the majority of coal samples is between 1 to 4 ppm. This is within the range of other publications [14], [15]. There are some coals with much higher contents of radionuclides, but these are very rare. Therefore, a low case and a high case are

	Mass of equipment tons	Activated waste tons	Life time years	Number of replacements	Number of disposals
Total outer layers	50,004	50,004			
Toroidal field coils	42,605	42,605	25	0	1
Vaccuum vessel	6,927	6,927	25	0	1
Outer manifold	472	472	25	0	1
Total blanket sections	5,551	18,068			
Low temperature shield	2,422	2,422	25	0	1
High temperature shield	1,684	8,421	5	4	5
Blanket with breeder zones	1,312	6,562	5	4	5
First wall	132	662	5	4	5
Total divertor sections	659	6,586	2,5	9	10
Total	56,213	74,657			

Tab. 2. Masses of equipment and waste of fusion PPCS model B power plant.

Decimal point

Nuclide		U-235	U-238	Total
Specific figures for 1 ton of nuclide				
Specific acitivity	10^9 Bq/$t_{nuclide}$	879.6	174.0	
Specific ingestion hazard	10^3 Sv/$t_{nuclide}$	157.2	49.5	
Specific inhalation hazard	10^3 Sv/$t_{nuclide}$	57,334.6	1,790.5	
Content of radionuclides		0.042	0.958	
Specific figures for 1 ton of uranium				
Specific acitivity	10^9 Bq/$t_{uranium}$	36.9	166.7	203.7
Specific ingestion hazard	10^3 Sv/$t_{uranium}$	6.6	47.4	54.0
Specific inhalation hazard	10^3 Sv/$t_{uranium}$	2,408.1	1,715.3	4,123.3
Total figures				
Uranium consumption	tons			657.0
Total activity	10^{12} Bq	24.3	109.5	133.8
Total ingestion hazard	10^6 Sv	4.3	31.1	35.5
Total inhalation hazard	10^6 Sv	1,582.1	1,126.9	2,709.0

Tab. 3. Activity and radiotoxicity of enriched uranium.

Nuclide		Th-232	U-235	U-238	Total
Specific figures for 1 ton of nuclide					
Specific acitivity	10^9 Bq/$t_{nuclide}$	40.6	879.6	174.0	
Specific ingestion hazard	10^3 Sv/$t_{nuclide}$	4.3	157.2	49.5	
Specific inhalation hazard	10^3 Sv/$t_{nuclide}$	688.3	57,334.6	1,790.5	
LOW CASE					
Content of radionuclides	ppm	1	0.0071	0.9929	
Specific figures for 1 ton of coal, low case					
Specific acitivity	10^3 Bq/tc_{oal}	40.6	6.2	172.8	219.6
Specific ingestion hazard	10^{-3} Sv/tc_{oal}	4.3	1.1	49.1	54.6
Specific inhalation hazard	10^{-3} Sv/tc_{oal}	688.3	407.1	1,777.8	2,873.2
Total figures					
Coal consumption	mln tons				77.9
Total activity	10^{12} Bq	3.2	0.5	13.5	17.1
Total ingestion hazard	10^6 Sv	0.3	0.1	3.8	4.3
Total inhalation hazard	10^6 Sv	53.6	31.7	138.5	223.8
HIGH CASE					
Content of radionuclides	ppm	4	0.0284	3.9716	
Total figures					
Total activity	10^{12} Bq	12.6	1.9	53.8	68.4
Total ingestion hazard	10^6 Sv	1.3	0.3	15.3	17.0
Total inhalation hazard	10^6 Sv	214.5	126.9	554.0	895.3

Tab. 4. Coal composition, activity and radiotoxicity.

calculated, most coals being in between these limits. The low case is based on both a uranium and thorium content of 1 ppm, the high case on both a uranium and thorium content of 4 ppm of standard coal. As the origin of coal is since long time ago, the daughters of these nuclides are assumed to be in secular equilibrium to their parents. The content of other nuclides such as K-40 is neglected.

The secular equilibrium is calculated based on dose coefficients according to the 2001 update of EASY biological hazard data which are the same as those used for the fusion power plant. The results are shown in *Table 4*.

6. Comparison of power plant options

6.1 Masses of plutonium and americium

Uranium exists in a fusion power plant only in traces. The amount during power plant lifetime is by a factor of some 10,000 less than that used in a fission power plant. However, in a fusion power plant a relatively high share of some 30% is transmuted to plutonium and other actinides by the neutron profile, whereas in a fission power plant only some 3% of uranium is transmuted, of which some 2% is burnt and only some 1% is left in the waste as plutonium.

The waste produced within the lifetime of the fusion power plant contains some 23 kg of plutonium (of which 78% is Pu-239). This is approximately in line with the results of a publication of *Cambi* et. alt. [16] which report a total plutonium production of 4.9 kg in 5 full-load years, corresponding to 24.5 kg in 25 full-load years. This is by a factor of some 300 less compared to an open cycle fission power plant with 7.3 tons of plutonium (of which 53% is Pu-239). Moreover, the waste produced within the lifetime of the fusion power plant contains some 100 g of americium, compared to 460 kg of americium for the fission power plant.

6.2 Activity of waste

The development of activity of total wastes of a fusion power plant up to 10,000 years after end of lifetime, compared with a fission power plant and a coal-fired power plant, is shown in *Figure 4*. As waste output of a fission power plant an open cycle with no recycling, recycling of 99.5% of plutonium as well as recycling of 99.5% of plutonium and 90% of americium are shown. Additionally the activity of enriched uranium as input to the fission power plant is shown as a reference figure.

During the first 100 to 200 years, the activity of wastes from the PPCS model B fusion power plant is higher than the activity

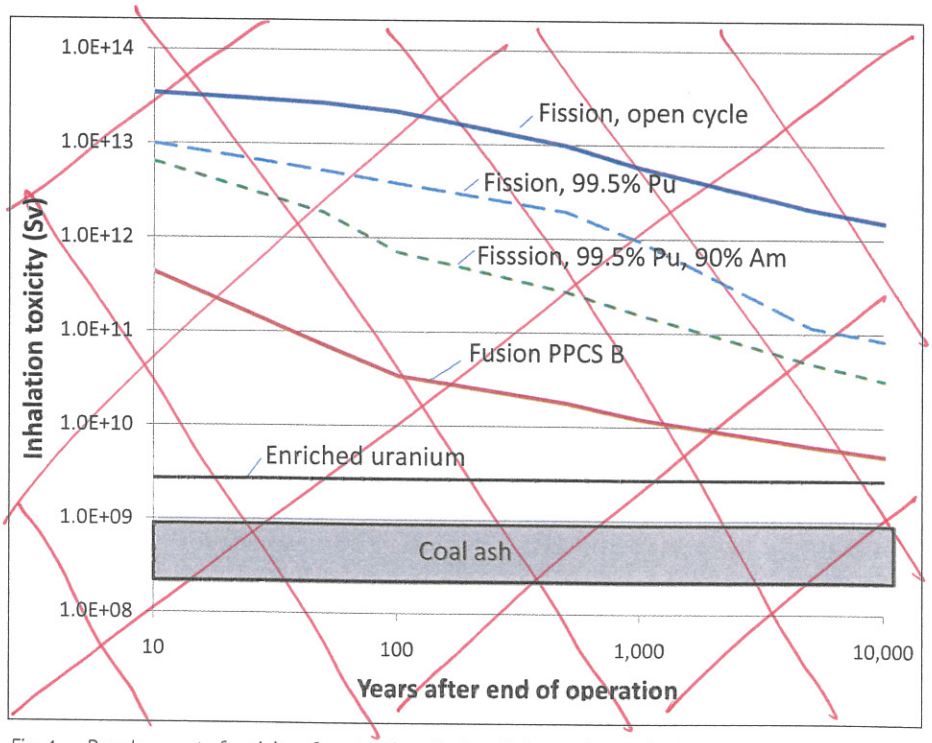
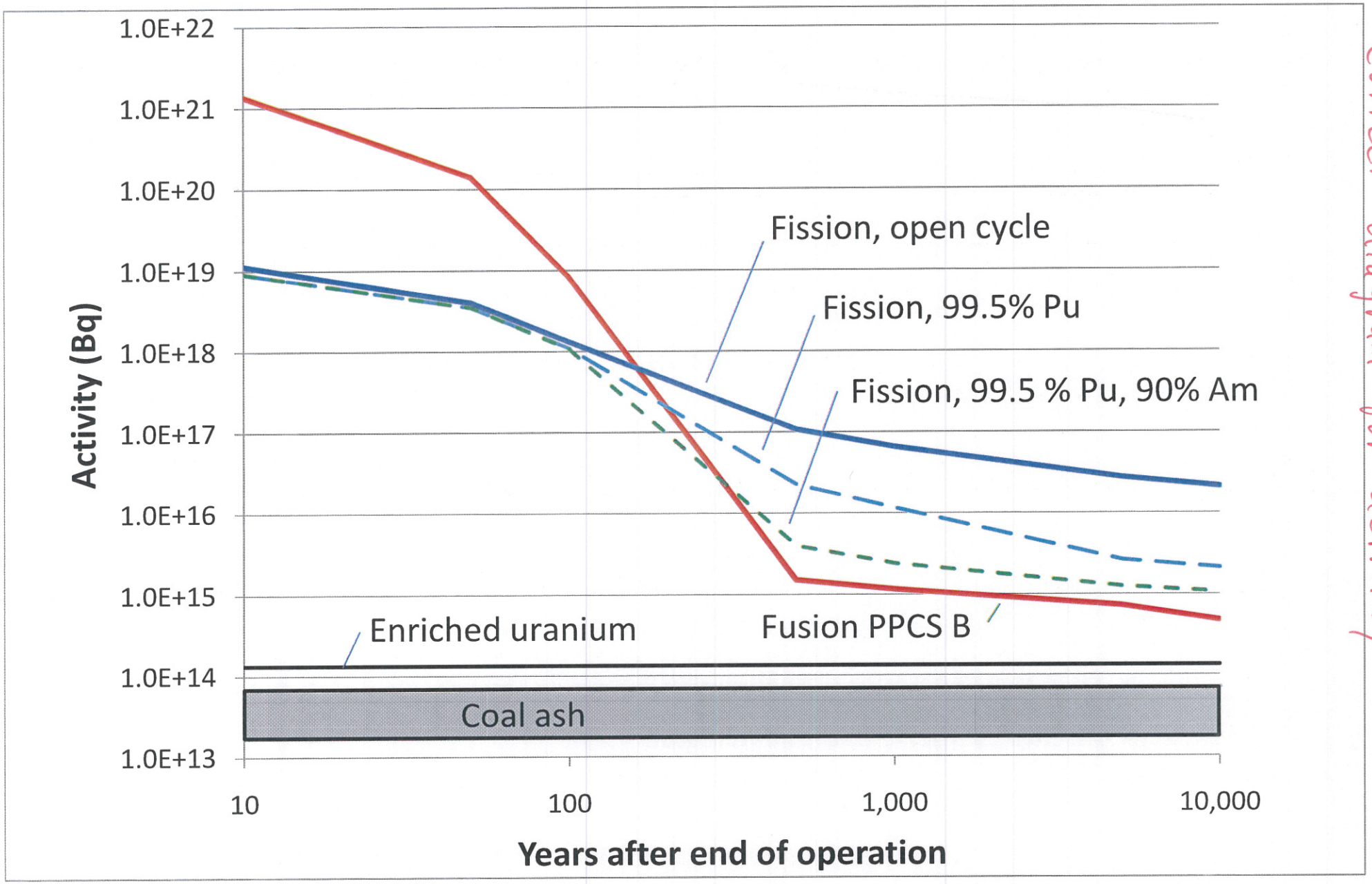


Fig. 4. Development of activity of wastes from fusion, fission and coal-fired power plants.

Wrong diagram inserted for activity



Correct diagram for activity